# A METHOD OF MEASURING MAGNETIC PROPERTIES OF FERROMAGNETIC AND OTHER SUBSTANCES

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**ABSTRACT** In connection with the study of the magnetic properties of Indian minerals, meteorites and various semiconductors which may be Ferro-, Antiferro-, Ferri-, Para- or Dia-magnetic at various temperatures, a horizontal translation type balance has been designed and constructed here. This balance is particularly suitable for measurements at high temperatures as convection disturbances are eliminated by having a horizontal oven Description and working of the balance are given in the paper

## INTRODUCTION

In connection with the study of the magnetic properties of certain Indian minerals and materials meteorites and various semiconductors which may be ferro.- antiferro,- ferri,-para- or diamagnetic, it has been observed that none of the magnetic balances used in this laboratory are suitable for measurements at high temperatures, —so essential for these studies. —owing to convection disturbances set up in the ovens Moreover, a method suitable for the said purpose should evidently be versatile, robust and at the same time sensitive A balance working on the principles of Foëx and Forrer (1926) with certain innovations has been found to meet the above requirements to a considerable extent. In such a balance the sample is attached at the end of a horizontal balance beam supported from a pair of bifilar suspensions with the sample arm protruding into a horizontal magnetic field with a gradient perpendicular to it in the same plane, so that the tubular heater enclosing the sample end of the beam is also to be placed in a horizontal position, thereby minimising disturbances due to convection currents Further, with such a balance not only the temperatures and the field variations, if any, of the above properties but the magnecrystallic anisotropy of the ferromagnetics can also be studied more reliably and conveniently than by other existing methods. The present communication gives a description and working of such a balance.

## THEORY

When any small crystalline body of permeability $\mu_{jk}$ surrounded by a isotropic medium of permeability $\mu_0$ is placed in a magnetic field $H$ it acquires magnetic potential energy given by (Nye, 1957)

$$V = -\frac{(\mu_{jk}-\mu_0)}{8\pi} H_j H_k$$

per unit volume, $j, k = 1, 2, 3$

Leaving for the present moment the intrinsic magnetic field within the megnetised body, the magnetic force acting on the small body of volume $v$ is then given by

$$F_i = -\frac{\partial}{\partial x_i} \frac{(-\mu_{jk}+\mu_0)}{8\pi} vH_j H_k$$

$$= v(K_{jk} - K_0) H_k \frac{\partial H_j}{\partial x_i}.$$

$$i, j, k = 1, 2, 3,$$

where $K_{jk}$ and $K_0$ are the volume susceptibilities of the specimen and the medium respectively

If the magnetic field is so arranged that, $\frac{\partial H_1}{\partial x_1} = \frac{\partial H_1}{\partial x_3} = 0$, $H_2 = H_3 = 0$ and further the crystal is set with its $K_1$ direction along $H_1$, then we are left with the sole component of the force given by

$$F_2 = v(K_1 - K_0) H_1 \frac{\partial H_1}{\partial x_2} \quad \text{.. (1)}$$

Now for a very small volume of a ferromagnetic substance of suitable shape for estimating the shape effect, placed in a field of very small constant gradient over the sample so that the field dependence of $K_1$ is negligible, the force (neglecting $K_0$ compared to large value of $K_1$ for a ferromagnetic sample) is

$$F_2 = I_1 \frac{\partial H_1}{\partial x_2} v \quad \text{... (2)}$$

where $I_1$ is the component of magnetic moment per unit volume of the substance. The above conditions are conveniently obtained in a Foëx—Forrer type of balance in which motion is allowed only in one particular direction in the horizontal plane with a specially shaped pole gap

## DESCRIPTION

The different parts of the balance are described concisely but with special reference to the modification of the standard Foëx-Forrer arrangement, in the following paragraphs and can be followed easily with reference to the adjoining diagram (fig.1.)

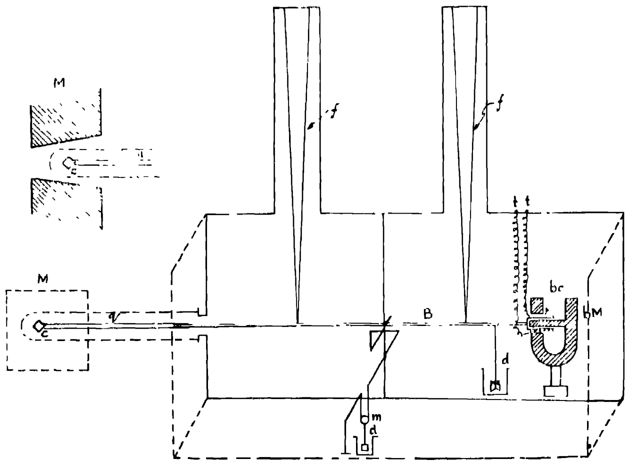


Fig 1. A sketch of the magnetic balance (not to the scale)

(a) *Balance beam* ($B$)

This is a thin uniform glass tube about 30 cms long and 0 3 cms in diameter suspended horizontally by a pair of fine glass bifilar suspensions $f$ from a height of about 60 cms the upper ends of the two fibres of each being fixed 21 cms apart. This allows the motion of the beam only in a horizontal direction perpendicular to the planes of the bifilar fibres and the horizontal magnetic field is here so arranged that it lies at right angles to, while its gradient lies along the above direction in which the beam is free to move At the end of the beam which slightly protrudes out of the balance case is attached a small length of quartz tube $q$ to the other end of which the specimen $c$ is to be attached The distance between the balance and the magnet $M$ is so adjusted that the specimen is always at a place within the pole gaps of the magnet where (i) $\frac{\partial H_1}{\partial x_2}$ is small and constant during the measurements with ferromagnetics or (ii) $H_1 \frac{\partial H_1}{\partial x_2}$ is constant during the measurements with non-ferromagnetics At the other end of the balance beam is attached coaxially a small solenoidal coil $bc$ of about 100 turns of superenamelled copper wire (42 S.W.G) which can freely move within specially designed poles (after Foëx and Forrer 1926) of a small permanent magnet $bM$. This arrangement is for balancing any force which is exerted at the other end of the balance beam.

(b) *Detection of movement of the balance beam.*

The movement of the balance beam and restoration of its position is observed by a light spot on a scale reflected from a mirror *m* suspended by means of a bi-filar arrangement attached at the other end of a thin glass lever rod *l* connected by a short length of quartz fibre to the balance beam

(c) *Damping* (*d*)

Proper damping arrangements have been made for the balance beam and the bifilar mirror. These are mica vanes, hanging from the balance beam and the mirror immersed in light oil kept in appropriate dash pots

(d) *The magnet* (*M*)

The theoretical condition for measurements on ferromagnetics, that is a constant gradient transverse to the magnetic field and over a considerable region, is provided for here by having a proper angle ($\sim 6^\circ$) between the two large rectangular pole pieces of the electromagnet (10 cm $\times$ 11 cm) for a particular pole gap (5 7 cm at the central region) The field was measured at intervals of 2 mm. throughout the length of the pole gap at right angles to the field by a sensitive fluxmeter. From the graphs showing the variations of the field with distance the most useful region was selected which showed small and steady variations of the field. Such graphs (Fig 2.) have also been obtained for different exciting currents of the magnet so that measurements on different samples can easily be taken at different fields.

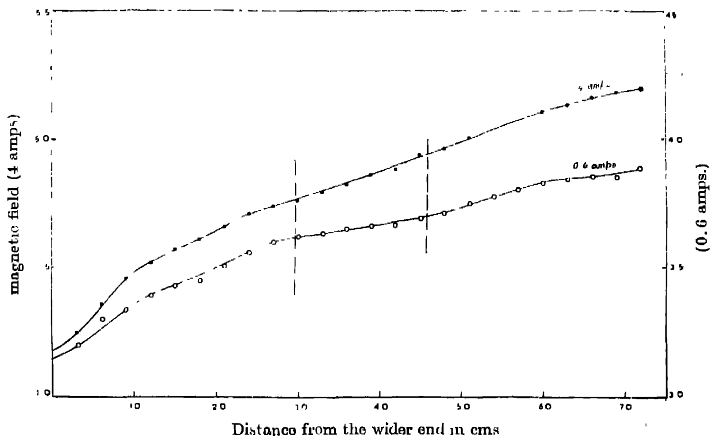


Fig. 2 Variation of the magnetic field with distance from the wider end along the length of the pole gap in arbitrary units.

For non-ferromagnetic substances two Sucksmith types of pole shoes (Sucksmith 1929) are to be attached in the usual way to the pole pieces so that the necessary conditions of uniform $H_1 \frac{\partial H_1}{\partial x_2}$ is obtained Switching, reversing, controlling, and reading arrangements for the magnet current are the same as already adopted here (Dutta Roy 1955).

(c) *Working of the balance*

(i) Measurement of magnetic force and test of sensitiveness

As pointed out earlier, the magnetic force exerted on the specimen placed at one end of the beam is balanced by sending a suitable current through the coil at the other end. Now the magnetic forces per unit volume on different samples are proportional to their susceptibilities but it is also necessary to check whether the balancing currents in the coil are exactly proportional to the magnetic forces, since balancing forces upon the coil may depend in a complicated way upon the geometry of the system In order to ascertain this point and also find the limit of sensitiveness of the balance the following experiment was performed.

An unspun silk fibre connected to the sample end of the balance beam runs horizontally over a jewel pivoted pulley having almost no friction at the bearings, from which weights varying from 1 m.gm to 100 m.gm are successively suspended This caused a forward motion of the beam and the light spot from the mirror is widely deflected. It is brought back to its initial position by sending a requisite current through the balancing coil. The current is indicated by a sensitive and accurate milli-or micro-ammeter put in the circuit. The actual value of the current was however obtained by measuring the drop of potential across a standard resistance. The results of the measurement are represented graphically in Fig. 3

It will be seen from the graph that the balancing current is accurately directly proportional to the force acting at the other end. Also it is observed that the sensitiveness of the balance with the present coil is about $1.25 \times 10^{-5}$gms./$\mu A$ which however can be further increased by changing the number of turns of the coil.

## CALIBRATION

(a) *For ferromagnetics*

Since the ferromagnetic susceptibility is field dependent the usual method of using a standard substance for calibrating the balance is not applicable. This has, however, been overcome by using instead a coil of known dimension and number of turns attached at other end of the quartz tube ($q$), so that the coil is at the same position within the poles of the magnet ($M$) where there is small and constant gradient, the axis of the coil being parallel to magnetic field direction

A known current is passed through it which is read by a calibrated milliammeter. When the magnet is switched on a force acts on this coil and can be balanced by passing current through the balancing coil (*bc*).

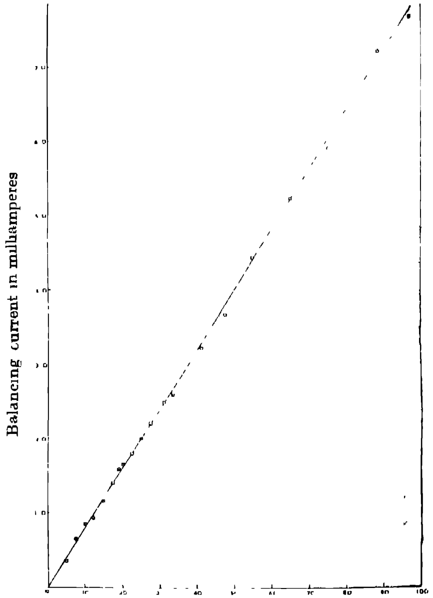


Fig 3. Load-Balancing current curve for a particular balancing coil

For the purpose of actual measurement the specimen is first attached at the end of the quartz tube (*q*) and the magnetic force is balanced by passing a current say $i_1$ through the balancing coil Now the specimen is replaced by the standardising coil mentioned above and the magnetic force is balanced at the same value of the magnetic field as that of the specimen by passing a current $i_2$, through the coil (*bc*). Then the intensity of magnetisation, $I$, of the specimen is given by (from eq. 2)

$$I_s = \frac{i_1}{i_2} \; \frac{NAc\rho}{m}$$

where $N$ is the total number of turns of the standardising coil, $A$ the area of the section of the coil, $c$ the current through it. $\rho$ the density and $m$ the mass of the specimen.

As a test measurement different currents were passed through such a coil and the force exerted on it when the magnetic field is switched on is balanced in the usual way by sending appropriate currents through the balancing coil

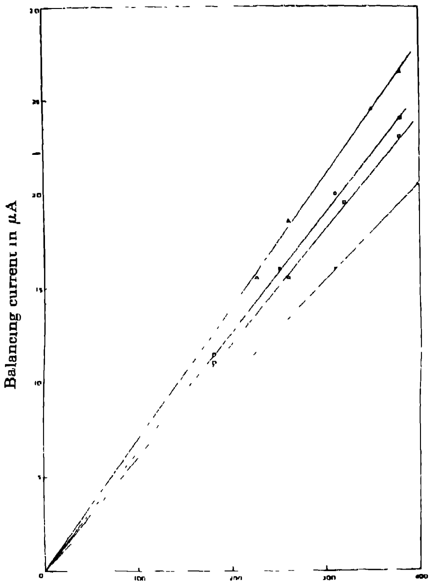


Fig 4 Balancing current for different currents in the standardising coil at different magnetic fields. Coil I 1780 oe ● ; 2050 oe ⊗ ; coil II 1780 oe □; 2050 oe .

This procedure is repeated for different magnetic fields and with coils having different number of turns. The results of measurement are shown in Fig 4 The relationship between the current through the standardising coil (i.e. its moment) and the current in the balancing coil (i e. the force exerted on the standardising coil) is a linear one for a fixed value of the field. Thus in order to find the field variation of the magnetisation of the ferromagnetic specimen, the force acting on it and the standardising coil with known current flowing through it (i.e. the respective balancing currents) are compared at the different desired fields.

(b) *For non-ferromagnetics*

For non-ferromagnetics, as has been pointed out above, two Sucksmith type of pole shoes are attached over the flat pole pieces of the magnet and the magnetic force exerted on the specimen and on the standard substance, both placed in the same position within the pole gaps with uniform $H_1 \frac{\partial H_1}{\partial x_2}$ over considerable region, are successively balanced by sending currents through the balancing coil, when one is replaced by the other Then the mass susceptibility of the specimen is given by (from eq. 1)

$$\chi = \frac{i}{i_s} \frac{m_s}{m} \left( \chi_s - \frac{K_a}{\rho_s} \right) + \frac{K_a}{\rho}$$

where $\chi_s$ is the mass susceptibility of the standard substance, $i$ and $i_s$ the balancing currents for the specimen and the standard substance respectively, $m$ and $m_s$ the corresponding masses, $\rho$ and $\rho_s$ the densities and $K_a$ the volume susceptibility of the surrounding medium i.e., air at the temperature at which the measurements were taken

For checking the reliability of the balance so far as the non-ferromagnetics are concerned the susceptibilities of a number of freshly prepared crystals of Ferric ammonium Alum ($Fe_2(SO_4)_3(NH_4)_2SO_4 \cdot 24.H_2O$) grown from aqueous solution using G.R quality samples of E. Merck were measured using a crystal of Chrome Potassium Alum ($Cr_2(SO_4)_3K_2SO_4 \cdot 24H_2O$) grown in the same way as

TABLE 1

$p^2_{eff}$ for $Fe^{3+}$ Alum

| | Standard | Unknown | Earlier values for $p^2_{eff}$ of the unknown sample at 300°K |
|---|---|---|---|
| Substance | $Cr^{3+}$ Alum | $Fe^{3+}$ Alum | |
| Density | 1.842 gms/c.c | 1.724 gms/c.c. | |
| Mass | 15720 gms | 09020 gms | |
| Balancing current | 127.0 $\mu$A | 180.0 $\mu$A | |
| $\chi \times 10^6$ | 11.98 at 300°K | 29.56 at 300°K | |
| $p^2_{eff}$ (in Bohr magneton units) | 14.91 | 34.75 | 34.80 (Dutta Roy 1955, 1956) |
| | | | 35.0 (Spin only value) |
| Substance | $NiCl_2$ Soln. | $Fe^{3+}$ Alum. | |
| Density | 1.2993 gms/c.c | 1.724 gms/c.c | 34.60 (Onnes and Oosterhuis 1927) |
| Mass | 33400 gms, of concentration 2590 gms. of $NiCl_2$ per gms. of soln | 07245 gms | |
| Balancing current | 280.0 $\mu$A. | 225.0 $\mu$A | |
| $\chi \times 10^6$ | 8.1067 at 302°K | 29.60 at 302°K | |
| $p_{eff}^2$ (in Bohr magneton units) | — | 34.79 | |

above, as a standard The results of measurements are shown in Table I and are found to agree well with other reported values, and are very consistent amongst themselves for a number of different samples Also the susceptibility of $Fe^{3+}$ Alum was determined using a nickel chloride ($NiCl_2$) solution of known strength as a standard and the result was found in agreement with standard values.

## CONCLUDING REMARKS

It is found that the balance described above is very convenient for measurements of a variety of substances of widely different susceptibilities both ferromagnetic and nonferromagnetic A horizontal cryostat or an oven eliminating convectional disturbances is very suitable for use with this balance The stability, reproducibility, and sensitivity are very high and it is now planned to start measurements on some natural ferromagnetic minerals such as ilmenite, magnetite etc., both above and below their Curie temperatures and especially in the region close to this temperature

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